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INTEGRATED QUANTUM COLD POINT COOLERS

BACKGROUND OF THE INVENTION

1. Technical Field:

The present invention relates to devices for cooling substances such as, for example, integrated circuit chips, and more particularly, the present invention relates to thermoelectric coolers.

2. Description of Related Art:

As the speed of computers continues to increase, the amount of heat generated by the circuits within the computers continues to increase. For many circuits and applications, increased heat degrades the performance of the computer. These circuits need to be cooled in order to perform most efficiently. In many low end computers, such as personal computers, the computer may be cooled merely by using a fan and fins for convective cooling. However, for larger computers, such as main frames, that perform at faster speeds and generate much more heat, these solutions are not viable.

Currently, many main-frames utilize vapor compression coolers to cool the computer. These vapor compression coolers perform essentially the same as the central air conditioning units used in many homes. However, vapor compression coolers are quite mechanically complicated requiring insulation and hoses that must run to various parts of the main frame in order to cool the particular areas that are most susceptible to decreased performance due to overheating.

A much simpler and cheaper type of cooler are thermoelectric coolers. Thermoelectric coolers utilize a physical principle known as the Peltier Effect, by which DC current from a power source is applied across two dissimilar materials causing heat to be absorbed at the junction of the two dissimilar materials. Thus, the heat is removed from a hot substance and may be transported to a heat sink to be dissipated, thereby cooling the hot substance. Thermoelectric coolers may be fabricated within an integrated circuit chip and may cool specific hot spots directly without the need for complicated mechanical systems as is required by vapor compression coolers.

However, current thermoelectric coolers are not as efficient as vapor compression coolers requiring more power to be expended to achieve the same amount of cooling. Furthermore, current thermoelectric coolers are not capable of cooling substances as greatly as vapor compression coolers. Therefore, a thermoelectric cooler with improved efficiency and cooling capacity would be desirable so that complicated vapor compression coolers could be eliminated from small refrigeration applications, such as, for example, main frame computers, thermal management of hot chips, RF communication circuits, magnetic read/write heads, optical and laser devices, and automobile refrigeration systems.

SUMMARY OF THE INVENTION

The present invention provides a method for forming a thermoelement for a thermoelectric cooler. In one embodiment a first substrate having a plurality of pointed tips separated by valleys wherein the substrate is covered by a metallic layer, portions of the metallic layer is covered by an insulator, and other portions of the metallic layer are exposed is formed. The other portions of the metallic layer that are exposed are covered with a thermoelectric material overcoat. A second substrate of thermoelectric material is then fused to the pointed tip side of the first substrate by, for example, heating the back of the first substrate to melt the thermoelectric material overcoat or by passing current through the pointed tips to induce Joule heating and thereby melt the thermoelectric material overcoat.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

Figure 1 depicts a high-level block diagram of a Thermoelectric Cooling (TEC) device in accordance with the prior art;

Figure 2 depicts a cross sectional view of a thermoelectric cooler with enhanced structured interfaces in accordance with the present invention;

Figure 3 depicts a planer view of thermoelectric cooler **200** in **Figure 2** in accordance with the present invention;

Figures 4A and **4B** depicts cross sectional views of tips that may be implemented as one of tips **250** in **Figure 2** in accordance with the present invention;

Figure 5 depicts a cross sectional view illustrating the temperature field of a tip near to a superlattice in accordance with the present invention;

Figure 6 depicts a cross sectional view of a thermoelectric cooler with enhanced structured interfaces with all metal tips in accordance with the present invention;

Figure 7 depicts a cross-sectional view of a sacrificial silicon template for forming all metal tips in accordance with the present invention;

Figure 8 depicts a flowchart illustrating an exemplary method of producing all metal cones using a silicon sacrificial template in accordance with the present invention;

Figure 9 depicts a cross sectional view of all metal cones formed using patterned photoresist in accordance with the present invention;

Figure 10 depicts a flowchart illustrating an exemplary method of forming all metal cones using photoresist in accordance with the present invention;

Figure 11 depicts a cross-sectional view of a thermoelectric cooler with enhanced structural interfaces in which the thermoelectric material rather than the metal conducting layer is formed into tips at the interface in accordance with the present invention;

Figure 12 depicts a flowchart illustrating an exemplary method of fabricating a thermoelectric cooler in accordance with the present invention;

Figure 13 depicts a cross-sectional diagram illustrating the positioning of photoresist necessary to produce tips in a thermoelectric material;

Figure 14 depicts a diagram showing a cold point tip above a surface for use in a thermoelectric cooler illustrating the positioning of the tip relative to the surface in accordance with the present invention;

Figure 15 depicts a schematic diagram of a thermoelectric power generator; and

Figures 16A-16J depict cross sectional diagrams illustrating a process for fabricating thermoelements with pointed tip interfaces in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference now to the figures and, in particular, with reference to **Figure 1**, a high-level block diagram of a Thermoelectric Cooling (TEC) device is depicted in accordance with the prior art. Thermoelectric cooling, a well known principle, is based on the Peltier Effect, by which DC current from power source **102** is applied across two dissimilar materials causing heat to be absorbed at the junction of the two dissimilar materials. A typical thermoelectric cooling device utilizes p-type semiconductor **104** and n-type semiconductor **106** sandwiched between poor electrical conductors **108** that have good heat conducting properties. N-type semiconductor **106** has an excess of electrons, while p-type semiconductor **104** has a deficit of electrons.

As electrons move from electrical conductor **110** to n-type semiconductor **106,** the energy state of the electrons is raised due to heat energy absorbed from heat source **112**. This process has the effect of transferring heat energy from heat source **112** via electron flow through n-type semiconductor **106** and electrical conductor **114** to heat sink **116**. The electrons drop to a lower energy state and release the heat energy in electrical conductor **114**.

The coefficient of performance, η, of a cooling refrigerator, such as thermoelectric cooler **100,** is the ratio of the cooling capacity of the refrigerator divided by the total power consumption of the refrigerator. Thus the coefficient of performance is given by the equation:

$$\eta = \frac{\alpha I T_c - \frac{1}{2} I^2 R - K \Delta T}{I^2 R + \alpha I \Delta T}$$

where the term $\alpha I T_c$ is due to the thermoelectric cooling, the term $\frac{1}{2} I^2 R$ is due to Joule heating backflow, the term $K\Delta T$ is due to thermal conduction, the term $I^2 R$ is due to Joule loss, the term $\alpha I \Delta T$ is due to work done against the Peltier voltage, α is the Seebeck coefficient for the material, T_c is the temperature of the heat source, and ΔT is the difference in the temperature of the heat source from the temperature of the heat sink.

The maximum coefficient of performance is derived by optimizing the current, I, and is given by the following relation:

$$\eta_{\max} = \left(\frac{T_c}{\Delta T}\right)\left[\frac{\gamma - T_h/T_c}{\gamma + 1}\right]$$

where

$$\gamma = \sqrt{1 + \frac{\alpha^2 \sigma}{\lambda}\left(\frac{T_h + T_c}{2}\right)}$$

and

$$\varepsilon = \frac{\gamma - T_h / T_c}{\gamma + 1}$$

where ε is the efficiency factor of the refrigerator. The figure of merit, ZT, is given by the equation:

$$ZT = \frac{\alpha^2 \sigma T}{\lambda}$$

where λ is composed of two components: λ_e, the component due to electrons, and λ_L, the component due to the lattice. Therefore, the maximum efficiency, ε, is achieved as the figure of merit, ZT, approaches infinity. The efficiency of vapor compressor refrigerators is approximately 0.3. The efficiency of conventional thermoelectric coolers, such as thermoelectric cooler **100** in **Figure 1**, is typically less than 0.1. Therefore, to increase the efficiency of thermoelectric coolers to such a range as to compete with vapor compression refrigerators, the figure of merit, ZT, must be increased to greater than 2. If a value for the figure of merit, ZT, of greater than 2 can be achieved, then the thermoelectric coolers may be staged to achieve the same efficiency and cooling capacity as vapor compression refrigerators.

With reference to **Figure 2**, a cross sectional view of a thermoelectric cooler with enhanced structured interfaces is depicted in accordance with the present

invention. Thermoelectric cooler **200** includes a heat source **226** from which, with current **I** flowing as indicated, heat is extracted and delivered to heat sink **202.** Heat source **226** may be thermally coupled to a substance that is desired to be cooled. Heat sink **202** may be thermally coupled to devices such as, for example, a heat pipe, fins, and/or a condensation unit to dissipate the heat removed from heat source **226** and/or further cool heat source **226.**

Heat source **226** is comprised of p- type doped silicon. Heat source **226** is thermally coupled to n+ type doped silicon regions **224** and **222** of tips **250.** N+ type regions **224** and **222** are electrical conducting as well as being good thermal conductors. Each of N+ type regions **224** and **222** forms a reverse diode with heat source **226** such that no current flows between heat source **226** and n+ regions **224** and **222,** thus providing the electrical isolation of heat source **226** from electrical conductors **218** and **220.**

Heat sink **202** is comprised of p- type doped silicon. Heat sink **202** is thermally coupled to n+ type doped silicon region **204.** N+ type region **204** is electrically conducting and is a good thermal conductor. N+ type region **204** and heat sink **202** forms a reverse diode so that no current flows between the N+ type region **204** and heat sink **202,** thus providing the electrical isolation of heat sink **202** from electrical conductor **208.** More information about electrical isolation of thermoelectric coolers may be found in commonly U.S. Patent No. 6,222,113, the contents of which are hereby incorporated herein for all purposes.

The need for forming reverse diodes with n+ and p- regions to electrically isolate conductor **208** from heat sink **202** and conductors **218** and **220** from heat source **226** is not needed if the heat sink **202** and heat source **226** are constructed entirely from undoped non-electrically conducting silicon. However, it is very difficult to ensure that the silicon is entirely undoped. Therefore, the presence of the reverse diodes provided by the n+ and p- regions ensures that heat sink **202** and heat source **226** are electrically isolated from conductors **208**, **218**, and **220**. Also, it should be noted that the same electrical isolation using reverse diodes may be created other ways, for example, by using p+ type doped silicon and n- type doped silicon rather than the p- and n+ types depicted. The terms n+ and p+, as used herein, refer to highly n doped and highly p doped semiconducting material respectively. The terms n- and p-, as used herein, mean lightly n doped and lightly p doped semiconducting material respectively.

Thermoelectric cooler **200** is similar in construction to thermoelectric cooler **100** in **Figure 1**. However, N-type **106** and P-type **104** semiconductor structural interfaces have been replaced with superlattice thermoelement structures **210** and **212** that are electrically coupled by doped region **204** and electrical conductor **208**. Electrical conductor **208** may be formed from platinum (Pt) or, alternatively, from other conducting materials, such as, for example, tungsten (W), nickel (Ni), or titanium copper nickel (Ti/Cu/Ni) metal films.

A superlattice is a structure consisting of alternating layers of two different semiconductor

materials, each several nanometers thick. Thermoelement **210** is constructed from alternating layers of N-type semiconducting materials and the superlattice of thermoelement **212** is constructed from alternating layers of P-type semiconducting materials. Each of the layers of alternating materials in each of thermoelements **210** and **212** is approximately 10 nanometers (nm) thick. A superlattice of two semiconducting materials has lower thermal conductivity, λ, and the same electrical conductivity, σ, as an alloy comprising the same two semiconducting materials.

In one embodiment, superlattice thermoelement **212** comprises alternating layers of p-type bismuth chalcogenide materials such as, for example, alternating layers of Bi_2Te_3/Sb_2Te_3 with layers of $Bi_{0.5}Sb_{1.5}Te_3$, and the superlattice of thermoelement **210** comprises alternating layers of n-type bismuth chalcogenide materials, such as, for example, alternating layers of Bi_2Te_3 with layers of Bi_2Se_3. Other types of semiconducting materials may be used for superlattices for thermoelements **210** and **212** as well. For example, rather than bismuth chalcogenide materials, the superlattices of thermoelements **210** and **212** may be constructed from cobalt antimony skutteridite materials.

Thermoelectric cooler **200** also includes tips **250** through which electrical current **I** passes into thermoelement **212** and then from thermoelement **210** into conductor **218**. Tips **250** includes n+ type semiconductor **222** and **224** formed into pointed conical structures with a thin overcoat layer **218** and **220** of conducting material, such as, for example, platinum (Pt). Other conducting

materials that may be used in place of platinum include, for example, tungsten (W), nickel (Ni), and titanium copper nickel (Ti/Cu/Ni) metal films. The areas between and around the tips **250** and thermoelectric materials **210** and **212** should be evacuated or hermetically sealed with a gas such as, for example, dry nitrogen.

On the ends of tips **250** covering the conducting layers **218** and **220** is a thin layer of semiconducting material **214** and **216**. Layer **214** is formed from a P-type material having the same Seebeck coefficient, α, as the nearest layer of the superlattice of thermoelement **212** to tips **250**. Layer **216** is formed from an N-type material having the same Seebeck coefficient, α, as the nearest layer of thermoelement **210** to tips **250**. The P-type thermoelectric overcoat layer **214** is necessary for thermoelectric cooler **200** to function since cooling occurs in the region near the metal where the electrons and holes are generated. The n-type thermoelectric overcoat layer **216** is beneficial, because maximum cooling occurs where the gradient (change) of the Seebeck coefficient is maximum. The thermoelectric overcoats **214** and **216** are preferably in the range of 2-5 nanometers thick based upon present investigation.

By making the electrical conductors, such as, conductors **110** in **Figure 1**, into pointed tips **250** rather than a planar interface, an increase in cooling efficiency is achieved. Lattice thermal conductivity, λ, at the point of tips **250** is very small because of lattice mismatch. For example, the thermal conductivity, λ, of bismuth chalcogenides is normally approximately 1 Watt/meter*Kelvin. However, in pointed tip structures,

such as tips **250**, the thermal conductivity is reduced, due to lattice mismatch at the point, to approximately 0.1 Watts/meter*Kelvin. However, the electrical conductivity of the thermoelectric materials remains relatively unchanged. Therefore, the figure of merit, *ZT*, may increased to greater than 2.5 for this kind of material. Another type of material that is possible for the superlattices of thermoelements **210** and **212** is cobalt antimony skutteridites. These type of materials typically have a very high thermal conductivity, λ, making them normally undesirable. However, by using the pointed tips **250**, the thermal conductivity can be reduced to a minimum and produce a figure of merit, *ZT*, for these materials of greater than 4, thus making these materials very attractive for use in thermoelements **210** and **212**.

Another advantage of the cold point structure is that the electrons are confined to dimensions smaller than the wavelength (corresponding to their kinetic energy). This type of confinement increases the local density of states available for transport and effectively increases the Seebeck coefficient. Thus, by increasing α and decreasing λ, the figure of merit ZT is increased.

Conventional thermoelectric coolers, such as illustrated in **Figure 1**, are capable of producing a cooling temperature differential, ΔT, between the heat source and the heat sink of around 60 Kelvin. However, thermoelectric cooler **200** is capable of producing a temperature differential greater than 100 Kelvin. Thus, with two thermoelectric coolers coupled to each other, cooling to temperatures in the range of liquid Nitrogen (less than 100 Kelvin) is possible. However, different

materials may need to be used for thermoelements **210** and **212**. For example, bismuth telluride has a very low α at low temperature (i.e. less than -100 degrees Celsius). However, bismuth antimony alloys perform well at low temperature.

Those of ordinary skill in the art will appreciate that the construction of the thermoelectric cooler in **Figure 2** may vary depending on the implementation taking into account the desired cooling, heat transfer capacity, current and voltage supplies. For example, more or fewer rows of tips **250** may be included than depicted in **Figure 1**. The depicted example is not meant to imply architectural limitations with respect to the present invention.

With reference now to **Figure 3**, a planer view of thermoelectric cooler **200** in **Figure 2** is depicted in accordance with the present invention. Thermoelectric cooler **300** includes an n-type thermoelectric material section **302** and a p-type thermoelectric material section **304**. Both n-type section **302** and p-type section **304** include a thin layer of conductive material **306** that covers a silicon body.

Section **302** includes an array of conical tips **310** each covered with a thin layer of n-type material **308** of the same type as the nearest layer of the superlattice for thermoelement **210**. Section **304** includes an array of conical tips **312** each covered with a thin layer of p-type material **314** of the same type as the nearest layer of the superlattice for thermoelement **212**.

With reference now to **Figures 4A** and **4B**, a cross sectional views of tips that may be implemented as one of

tips **250** in **Figure 2** is depicted in accordance with the present invention. Tip **400** includes a silicon cone **402** that has been formed with a cone angle of approximately 35 degrees. A thin layer **404** of conducting material, such as platinum (Pt), overcoats the silicon **402.** A thin layer of thermoelectric material **406** covers the very end of the tip **400.** The cone angle after all layers have been deposited is approximately 45 degrees. The effective point radius of tip **400** is approximately 50 nanometers.

Tip **408** is an alternative embodiment of a tip, such as one of tips **250.** Tip **408** includes a silicon cone **414** with a conductive layer **412** and thermoelectric material layer **410** over the point. However, tip **408** has a much sharper cone angle than tip **400.** The effective point radius of tip **408** is approximately 10 nanometers. It is not known at this time whether a broader or narrower cone angle for the tip is preferable. In the present embodiment, conical angles of 45 degrees for the tip, as depicted in **Figure 4A**, have been chosen, since such angle is in the middle of possible ranges of cone angle and because such formation is easily fabricated from silicon with a platinum overcoat. This is because a KOH etch along the <100> plane of silicon naturally forms a cone angle of 54 degrees. Thus, after the conductive and thermoelectric overcoats have been added, the cone angle is approximately 45 degrees.

With reference now to **Figure 5**, a cross sectional view illustrating the temperature field of a tip near to a superlattice is depicted in accordance with the present invention. Tip **504** may be implemented as one of tips **250**

in **Figure 2**. Tip **504** has a effective tip radius at its sharpest point, *a*, of 10-50 nanometers. Thus, the temperature field is localized to a very small distance, r, approximately equal to 2a or around 20-100 nanometers. Superlattice **502** need to be only a few layers thick to limit heat flow. Therefore, using pointed tips, a thermoelectric cooler with only 5-10 layers for the superlattice is sufficient.

Thus, fabricating a thermoelectric cooler, such as, for example, thermoelectric cooler **200**, is simplified, since only a few layers of the superlattice must be formed. Also, thermoelectric cooler **200** can be fabricated very thin (on the order of 100 nanometers thick) as contrasted to conventional thermoelectric coolers which are on the order of 3 millimeters or greater in thickness.

Other advantages of a thermoelectric cooler with pointed tip interfaces in accordance with the present invention include minimization of the thermal conductivity through the thermoelements, such as thermoelements **210** and **212** in **Figure 2**, because of the tip interfaces. Also, the temperature/potential drops are localized to an area near the tips, effectively allowing scaling to sub-100-nanometer lengths. Furthermore, using pointed tips minimizes the number layers needed for superlattice thermoelements **210** and **212**. The present invention also permits electrodeposition of thin film structures. The smaller dimensions also allow for monolithic integration of n-type and p-type thermoelements.

The thermoelectric cooler of the present invention may be utilized to cool items, such as, for example,

specific spots within a main frame computer, lasers, optic electronics, photodetectors, and PCR in genetics.

With reference now to **Figure 6**, a cross sectional view of a thermoelectric cooler with enhanced structured interfaces with all metal tips is depicted in accordance with the present invention. Although the present invention has been described above as having tips **250** constructed from silicon cones constructed from the n+ semiconducting regions **224** and **222**, tips **250** in **Figure 2** may be replaced by tips **650** as depicted in **Figure 6**. Tips **650** have all metal cones **618** and **620**. In the depicted embodiment, cones **618** and **620** are constructed from copper and have a nickel overcoat layer **660** and **662**. Thermoelectric cooler **600** is identical to thermoelectric cooler **200** in all other respects, including having a thermoelectric overcoat **216** and **214** over the tips **650**. Thermoelectric cooler **600** also provides the same benefits as thermoelectric cooler **200**. However, by using all metal cones rather than silicon cones covered with conducting material, the parasitic resistances within the cones become very low, thus further increasing the efficiency of thermoelectric cooler **600** over the already increased efficiency of thermoelectric cooler **200**. The areas surrounding the contact areas of tips **650** to thermoelectric materials **210** and **212** should be vacuum or hermetically sealed with a low-thermal conductivity gas, such as, for example, argon.

Also, as in **Figure 2**, heat source **226** is comprised of p- type doped silicon. In contrast to **Figure 2**, however, silicon heat source **226** is thermally coupled to n+ type doped silicon regions **624** and **622** but does not

form part of the tipped structure **650** as did silicon regions **224** and **222** do in **Figure 2**. N+ type doped silicon regions **624** and **622** do still perform the electrical isolation function performed by regions **224** and **222** in **Figure 2**.

Several methods may be utilized to form the all metal cones as depicted in **Figure 6**. For example, with reference now to **Figure 7**, a cross-sectional view of a sacrificial silicon template that may be used for forming all metal tips is depicted in accordance with the present invention. After the sacrificial silicon template **702** has been constructed having conical pits, a layer of metal may be deposited over the template **702** to produce all metal cones **704**. All metal cones **704** may then be used in thermoelectric cooler **600**.

With reference now to **Figure 8**, a flowchart illustrating an exemplary method of producing all metal cones using a silicon sacrificial template is depicted in accordance with the present invention. To begin, conical pits are fabricated by anisotropic etching of silicon to create a mold (step **802**). This may be done by a combination of KOH etching, oxidation, and/or focused ion-beam etching. Such techniques of fabricating silicon pits are well known in the art.

The silicon sacrificial template is then coated with a thin sputtered layer of seed metal, such as, for example, titanium (step **804**). Next, copper is electrochemically deposited to fill the valleys (conical pits) in the sacrificial silicon template. (step **806**). The top surface of the copper is then planarized (step **808**). Methods of planarizing a layer of metal are well

known in the art. The silicon substrate is then removed by selective etching methods well known in the art (step **810**). The all metal cones produced in this manner may then be covered with a coat of another metal, such as, for example, nickel, and then with an ultra-thin layer of thermoelectric material. The nickel overcoat aids in electrodeposition of the thermoelectric material overcoat.

One advantage to this method of producing all metal cones is that the silicon substrate mold is reusable if the copper is peeled from the silicon substrate as the separation process. The silicon substrate mold may be reused up to around 10 times before the mold degrades and becomes unusable.

Forming a template in this manner is very well controlled and produces very uniform all metal conical tips since silicon etching is very predictable and can calculate slopes of the pits and sharpness of the cones produced to a very few nanometers.

Other methods of forming all metal cones may be used as well. For example, with reference now to **Figure 9**, a cross sectional view of all metal cones **902** formed using patterned photoresist is depicted in accordance with the present invention. In this method, a layer of metal is formed over the bottom portions of a partially fabricated thermoelectric cooler. A patterned photoresist **904-908** is then used to fashion all metal cones **902** with a direct electrochemical etching method. Often the tips are further sharpened by focused ion beam milling.

With reference now to **Figure 10**, a flowchart illustrating an exemplary method of forming all metal cones using photoresist is depicted in accordance with the

present invention. To begin, small sections of photoresist are patterned over a metal layer, such as copper, of a partially fabricated thermoelectric cooler (step **1002**). The photoresist may be patterned in an array of sections having photoresist wherein each area of photoresist within the array corresponds to areas in which tips to the all metal cones are desired to be formed. The metal is then directly etched electrochemically (step **1004**) to produce cones **902** as depicted in **Figure 9**. The photoresist is then removed and the tips of the all metal cones may then be coated with another metal, such as, for example, nickel (step **1006**). The second metal coating over the all metal cones may then be coated with an ultra-thin layer of thermoelectric material (step **1008**). Thus, all metal cones with a thermoelectric layer on the tips may be formed which may used in a thermoelectric device, such as, for example, thermoelectric cooler **600**. The all metal conical points produced in this manner are not as uniform as those produced using the method illustrated in **Figure 8**. However, this method currently is cheaper and therefore, if cost is an important factor, may be a more desirable method.

The depicted methods of fabricating all metal cones are merely examples. Other methods may be used as well to fabricate all metal cones for use with thermoelectric coolers. Furthermore, other types of metals may be used for the all metal cone other than copper.

With reference now to **Figure 11**, a cross-sectional view of a thermoelectric cooler with enhanced structural interfaces in which the thermoelectric material rather than the metal conducting layer is formed into tips at the interface is depicted in accordance with the present

invention. Thermoelectric cooler **1100** includes a cold plate **1116** and a hot plate **1102**, wherein the cold plate **1116** is in thermal contact with the substance that is to be cooled. Thermal conductors **1114** and **1118** provide a thermal couple between electrical conducting plates **1112** and **1120** respectively. Thermal conductors **1114** and **1118** are constructed of heavily n doped (n+) semiconducting material that provides electrical isolation between cold plate **1116** and conductors **1112** and **1120** by forming reverse biased diodes with the p- material of the cold plate **1116.** Thus, heat is transferred from the cold plate **1116** through conductors **1112** and **1120** and eventually to hot plate **1102** from which it can be dissipated without allowing an electrical coupling between the thermoelectric cooler **1100** and the substance that is to be cooled. Similarly, thermal conductor **1104** provides a thermal connection between electrical conducting plate **1108** and hot plate **1102,** while maintaining electrical isolation between the hot plate and electrical conducting plate **1108** by forming a reverse biased diode with the hot plate **1102** p- doped semiconducting material as discussed above. Thermal conductor **1104** is also an n+ type doped semiconducting material. Electrical conducting plates **1108, 1112,** and **1120** are constructed from platinum (Pt) in this embodiment. However, other materials that are both electrically conducting and thermally conducting may be utilized as well. Also, it should be mentioned that the areas surrounding tips **1130-1140** proximate thermoelectric materials **1122** and **1110** should be evacuated to produce a vacuum or should be hermetically sealed with a low

thermal conductivity gas, such as argon.

In this embodiment, rather than providing contact between the thermoelements and the heat source (cold end) metal electrode (conductor) through an array of points having metal in the point electrodes as in **Figures 2** and **6**, the array of points of contact between the thermoelement and the metal electrode is provided by an array of points **1130-1140** composed of thermoelements **1124** and **1126**. The tips **1130-1140** of the present embodiment may be formed from single crystal or polycrystal thermoelectric materials by electrochemical etching.

In one embodiment, thermoelement **1124** is comprised of a super lattice of single crystalline Bi_2Te_3/Sb_2Te_3 and $Bi_{0.5}Sb_{1.5}Te_3$ and thermoelement **1126** is formed of a super lattice of single crystalline Bi_2Te_3/Bi_2Se_3 and $Bi_2Te_{2.0}Se_{0.1}$. Electrically conducting plate **1120** is coated with a thin layer **1122** of the same thermoelectric material as is the material of the tips **1130-1134** that are nearest thin layer **1120**. Electrically conducting plate **1112** is coated with a thin layer **1110** of the same thermoelectric material as is the material of the tips **1136-1140** that are nearest thin layer **1112**.

With reference now to **Figure 12**, a flowchart illustrating an exemplary method of fabricating a thermoelectric cooler, such as, for example, thermoelectric cooler **1100** in **Figure 11**, is depicted in accordance with the present invention. Optimized single crystal material is first bonded to a metal electrode **1301** by conventional means or the metal electrode is deposited onto the single crystal material to form the electrode connection pattern (step **1202**) as depicted in

Figure 13. The other side of the thermoelectric material **1314** is then patterned (step **1204**) by using photoresist **1302-1306** as a mask and the metal electrode as an anode in an electrochemical bath to etch the surface (step **1206**). The tips **1308-1312** as depicted in **Figure 13** are formed by controlling and stopping the etching process at appropriate times.

A second single crystal substrate is thinned by chemical-mechanical polishing and then electrochemically etching the entire substrate to nanometer films (step **1210**). The second ultra-thin substrate forms the cold end. The two substrates (the one with the ultra-thin thermoelectric material and the other with the thermoelectric tips) are then clamped together with light pressure (step **1212**). This structure retains high crystallinity in all regions other than the interface at the tips. Also, similar methods can be used to fabricate polycrystalline structures rather than single crystalline structures.

With reference now to **Figure 14**, a diagram showing a cold point tip above a surface for use in a thermoelectric cooler illustrating the positioning of the tip relative to the surface is depicted in accordance with the present invention. Although the tips, whether created in as all-metal or metal coated tips or as thermoelectric tips have been described thus far as being in contact with the surface opposite the tips. However, although the tips may be in contact with the opposing surface, it is preferable that the tips be very near the opposing surface without fully touching the surface as depicted in **Figure 14**. The tip **1402** in **Figure 14** is situated near the opposing surface **1404** but is not in

physical contact with the opposing surface. Preferably, the tip **1402** should be a distance **d** on the order of 1 nanometer or less from the opposing surface **1404**. In practice, with a thermoelectric cooler containing thousands of tips, some of the tips may be in contact with the opposing surface while others are not in contact due to the deviations from a perfect plane of the opposing surface.

By removing the tips from contact with the opposing surface, the thermal conductivity between the cold plate and the hot plate of a thermoelectric cooler may be reduced. Electrical conductivity is maintained, however, due to tunneling of electrons between the tips and the opposing surface.

The tips of the present invention have also been described and depicted primarily as perfectly pointed tips. However, as illustrated in **Figure 14**, the tips in practice will typically have a slightly more rounded tip as is the case with tip **1402**. However, the closer to perfectly pointed the tip is, the fewer number of superlattices needed to achieve the temperature gradient between the cool temperature of the tip and the hot temperature of the hot plate.

Preferably, the radius of curvature $\mathbf{r}_0$ of the curved end of the tip **1402** is on the order of a few tens of nanometers. The temperature difference between successive layers of the thermoelectric material below surface **1404** approaches zero after a distance of two (2) to three (3) times the radius of curvature $\mathbf{r}_0$ of the end of tip **1402**. Therefore, only a few layers of the super lattice **1406-1414** are necessary. Thus, a superlattice material opposite the tips is feasible when the

electrical contact between the hot and cold plates is made using the tips of the present invention. This is in contrast to the prior art in which to use a superlattice structure without tips, a superlattice of 10000 or more layers was needed to have a sufficient thickness in which to allow the temperature gradient to approach zero. Such a number of layers was impractical, but using only 5 or 6 layers as in the present invention is much more practical.

Although the present invention has been described primarily with reference to a thermoelectric cooling device (or Peltier device) with tipped interfaces used for cooling, it will be recognized by those skilled in the art that the present invention may be utilized for generation of electricity as well. It is well recognized by those skilled in the art that thermoelectric devices can be used either in the Peltier mode (as described above) for refrigeration or in the Seebeck mode for electrical power generation. Referring now to **Figure 15**, a schematic diagram of a thermoelectric power generator is depicted. For ease of understanding and explanation of thermoelectric power generation, a thermoelectric power generator according to the prior art is depicted rather than a thermoelectric power generator utilizing cool point tips of the present invention. However, it should be noted that in one embodiment of a thermoelectric power generator according to the present invention, the thermoelements **1506** and **1504** are replaced cool point tips, as for example, any of the cool point tip embodiments as described in greater detail above.

In a thermoelectric power generator **1500**, rather than running current through the thermoelectric device

from a power source **102** as indicated in **Figure 1**, a temperature differential, T_H-T_L, is created across the thermoelectric device **1500.** Such temperature differential, T_H-T_L, creates a current flow, I, as indicated in **Figure 15** through a resistive load element **1502.** This is the opposite mode of operation from the mode of operation described in **Figure 1**

Therefore, other than replacing a power source **102** with a load resistor **1502** and maintaining heat elements **1512** and **1516** at differential temperatures T_H and T_L respectively with heat sources Q_H and Q_L respectively, thermoelectric device **1500** is identical in components to thermoelectric device **102** in **Figure 1.** Thus, thermoelectric cooling device **1500** utilizes p-type semiconductor **1504** and n-type semiconductor **1506** sandwiched between poor electrical conductors **1508** that have good heat conducting properties. More information about thermoelectric electric power generation may be found in <u>CRC Handbook of Thermoelectrics</u>, edited by D. M. Rowe, Ph.D., D.Sc., CRC Press, New York, (1995) pp. 479-488 and in <u>Advanced Engineering Thermodynamics</u>, 2nd Edition, by Adiran Bejan, John Wiley & Sons, Inc., New York (1997), pp. 675-682, both of which are hereby incorporated herein for all purposes.

With reference now to **Figures 16A-16J**, cross sectional diagrams illustrating a process for fabricating thermoelements with pointed tip interfaces is depicted in accordance with the present invention. The thermoelements fabricated with this method may be used as thermoelements for a thermoelectric cooler such as, for example, thermoelectric cooler **200.** To begin, a pointed

tip substrate **1602** such as, for example, a silicon substrate or copper substrate peeled from silicon molds as described above, is formed as depicted in **Figure 16A.** Next, the pointed tip substrate **1602** is coated with a metal layer **1604**, such as, for example, titanium (Ti) or platinum (Pt), by, for example, a sputtering or an evaporation process, as depicted in **Figure 16B.** A thin insulator **1606**, such as, for example, silicon dioxide, is deposited over the metal layer **1604** as depicted in **Figure 16C.** The valleys between tips **1610-1612** are filled with a sacrificial planarizing dielectric **1608** such that only the tips **1610-1612** of the metallic and insulator coated pointed tip substrate **1602** is exposed as depicted in **Figure 16D.**

Next, the sacrificial dielectric **1608** and thin insulator **1606** are etched together until the tips **1610-1612** are exposed as depicted in **Figure 16E.** A thermoelectric material overcoat **1613-1615** is then selectively grown by electrochemical methods or chemical vapor deposition (CVD) over the tips **1610-1612** to a thickness of approximately five (5) nanometers as depicted in **Figure 16F.** The sacrificial dielectric **1608** is then removed as depicted in **Figure 16G.** The pointed tip substrate **1602** with pointed tips **1610-1612** is mechanically aligned with a substantially flat surfaced thermoelectric substrate **1617** as depicted in **Figure 16H.** The single crystal thermoelectric substrate **1617** is polished on one side **1619** and metallized by sputter deposition of Ni **1618** on the opposite side. The end of pointed tip substrate **1602** opposite pointed tips **1610-1612** is heated to approximately 550 degrees Celsius

in order to melt the TE overcoats **1613-1615** and fuse the TE materials on the tips **1610-1612** to thermoelectric substrate **1617** as depicted in **Figure 16I.** Alternatively, a current may be passed through the tips **1610-1612** to the point that Joule heat melts the thermoelectric material **1613-1615** near the tips **1610-1612** in order to fuse the tips **1610-1612** to thermoelectric substrate **1617.**

The present invention has been described primarily with reference to conically shaped tips, however, other shapes of tips may be utilized as well, such as, for example, pyramidically shaped tips. In fact, the shape of the tip does not need to be symmetric or uniform as long as it provides a discrete set of substantially pointed tips through which electrical conduction between the two ends of a thermoelectric cooler may be provided. The present invention has applications to use in any small refrigeration application, such as, for example, cooling main frame computers, thermal management of hot chips and RF communication circuits, cooling magnetic heads for disk drives, automobile refrigeration, and cooling optical and laser devices.

The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. The embodiment was chosen and described in order to best explain the principles of the invention, the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.